Astro 596/496 PC

Lecture 41

May 5, 2010

Announcements:

- Final problem set, due at noon, Thrusday May 13
  open book+notes+web, but please do not collaborate
- PS 4-6?? bad grader! bad!
  scores posted by this Friday
  returned to grad mailboxes or pick up from me

Last time: cosmology with gravitational lensing

Q: lensing difficult to measure–why is it still a crucial tool?

Sketch of Lensing Physics

General setup: background source, foreground lens
lens distortion maps source plane into image plane
mapping depends on both source, lens

Spherical mass distribution: $\alpha(b) = 4GM(< b)/c^2 b$
aligned source–lens–obs: Einstein ring in image plane
otherwise: multiple arcs, symmetric about S-L axis on sky

General mass distribution: no symmetry
α set by lens projected surface mass density
$\Sigma(\vec{r}_\perp) = \int_{\rm los} \rho(\vec{r}_\perp, z) dz$; $\alpha(r_\perp) \sim \int dr \Sigma(r)$

Observable Effects

- amplification ("convergence") from symmetric piece of Φ
- shear from asymmetric piece of Φ

Weak Lensing and Large-Scale Structure

In fact, U. has density inhomogeneities on all scales
▷ $\delta(x)$ field lenses all objects!
▷ if measure effects over $z \to$ tomographic "slices"
$\Rightarrow$ recover 3-D map of cosmic matter distribution!
and more! power spectrum, correlation function, ...

But: the effects are small and subtle–*weak* lensing
- amplification non-trivial to measure
- shear more promising: circular gal $\to$ elliptical
  but elliptical $\to$ elliptical too!
  $\Rightarrow$ need statstical sample

Status: preliminary attempts done
future large surveys planned specifically for lensing `www: LSST`

Pro: no luck needed
Con: need large datasets, great care over systematics

In Search of the Intergalactic Medium

Quasars and the Gunn-Peterson Effect

Quasars excellent cosmic beacons $\longrightarrow$ use a backlighting
intervening neutral hydrogen absorbs all photons
wth $E_\gamma > 13.6$ eV $\Rightarrow$ in absorber rest frame

- "Lyman edge" $\lambda_{\mathrm{Ly}} < 912$ Å

Gunn & Peterson (1965): look for absorption trough
below "Lyman limit" $\lambda < (1 + z_{\mathrm{qso}})\lambda_{\mathrm{Ly}}$
i.e., integalactic H atoms should make U *opaque*
to these UV photons

but can detect QSO photons in this regime!
UV trough *no seen* out to $z \sim 5 - 6$!

Q: implications for IGM?
Q: what is actually seen? implications?

The Reionized Intergalactic Medium

Rather than uniform Gunn-Peterson trough, see Lyman-α forest implied mass in neutral H small:

$$\Omega_{\rm HI} \simeq 10^{-7} \ll \Omega_{\rm baryon} \tag{1}$$

▷ most baryons must be highly ionized at $z \gtrsim 6$: $1 - X_e \sim 10^{-5}$!
▷ the universe was somehow **reionized** by then
▷ IGM contains islands of neutral gas in ocean of ionized H

When was reionization?

recent evidence for reionization commencement!

⋆ SDSS discovery of $z \sim 6$ quasars with G-P trough

⋆ reionization $\rightarrow$ free e^- $\rightarrow$ CMB scattering, pol'n (à la SZ)

non-primordial fluctuation source at reionization

observe at large scales

WMAP 2003: reionization at $z = 10.9^{+2.7}_{-2.3}$ if instant

optical depth $\tau_{\rm reion} = \sigma_{\rm T} \int_{d_H} n_e ds \sim 0.17$ constrains ion history

Hydrogen reionization: Energetics

enormous energy injection required: $\gtrsim 13.6$ eV/baryon

Helium reionization

He II= $\rm He^{+1}$ reionization requires $Z^2_{\rm He} E_{1,\rm H} = 54.4$ eV photons

$\Rightarrow$ even more energetic photons needed

⋆ recent observations: He reionization at $z_{\rm He} \sim 3$

Q: Whodunit–candidates for reionization?

Reionization Candidates

The First Quasars

- very luminous
- flat spectra $\longrightarrow$ bright in UV photons
  promising candidates for helium reionization
- but relatively rare, and emission highly beamed

The First Stars

- more numerous than quasars
- if massive, also very luminous and UV-bright
  less promising for helium reionization

These hints about the IGM demand an understanding
of baryonic evolution of the universe
from the largest scales down to the formation of stars

The Cosmic History of Star Formation

history of cosmic star formation encodes a wealth of information:

- baryonic matter cycling: gas $\leftrightarrow$ stars, remnants
- energy exchange/feedback: starlight, supernova blasts
- element production ("chemical evolution")
- high-energy stellar events: supernovae, gamma-ray bursts

nice property of stars: they light up!
$\rightarrow$ can hope to measure cosmic star formation *directly*
by imaging the stars

Q: which stars trace current/*recent star formation?*
what (rest-frame) wavelengths/bands would trace these?

Q: so how can we mesure the cosmic star formation history?

Decoding The Cosmic Star-Formation Rate

recall: stellar lifetimes strongly decrease with mass
roughly $\tau_m \sim 10$ Gyr $(1\, M_\odot/m)^3$

high-mass stars are short-lived: die "instantly"
trace "instantaneous" star formation rate
bonus: massive stars also the most luminous

- dominate broadband *blue*, *UV* light from galaxies
- also power H II regions, traced by Hα

$\Rightarrow$ in individual galaxies: luminosity in each of these tracers
gives galactic star formation rate
$\Rightarrow$ cosmic luminosity *density* of each tracer
gives cosmic star formation rate at each z

`www: Observed Cosmic Star Fromation Rate`
Q: impressions? questions raised by this behavior?

The Cosmic Star-Formation Rate Observed

quantity plotted: cosmoving rate density of mass going into stars in rest frame, i.e.,

$$\dot{\rho}_\star(z) = \frac{dM_\star}{dt_{\rm em}\, dV_{\rm comov}} \tag{2}$$

key observed features:

- rise from present $z = 0$ value to peak at $z \sim 1 - 2$
- peak rate ~ 10 times higher than today
  $\rightarrow$ star formation is on the decline!
- behavior at $z \gtrsim 2$ uncertain

Open Questions:

- why is there a peak? why at $z \sim 1 - 2$?
- what is behavior at high z?
- how does the observed rate encode the interplay of star formation physics and structure/galaxy formation?

Finale: The Universe and Beyond the Infinite

Physical Cosmology: Present Status

A Sampler of Presently Open Questions in Cosmology

- What is the nature of dark matter? Can we detect it? Is dark matter relic particles left over from the early U.?

- What is the nature of the dark energy? Is it related to inflation?

- Did the universe undergo inflation? If so, what was the microphysics at work–i.e., what was the inflaton ϕ? If not, what is the origin of density fluctuations, and what solves the horizon and flatness problems?

- Did the universe undergo a singularity at $t = 0$? What is the nature of quantum gravity and what does this mean for the origin of the U.?

- What is the long-term fate of the universe?

- What is the geometry of the universe? the topology?

- What is the nature of the first stars? What role do they play in reionization? nucleosynthesis? the origin of supermassive black holes?

- What is the distribution of matter–all matter–in the universe? How do the cosmic components–baryons, DM, neutrinos, DE–contribute to the growth of structures? How is this written into galaxy evolution?

- Do astrophyiscal magnetic fields have a cosmological origin? Did the early universe play a role?

- How many of these questions are answerable?

- Are we fooling ourselves? Does modern cosmology contain epicycles which our grandchildren will find quaint? Is there some basic physics we have totally missed and awaits discovery?

COSMIC PREDICTIONS

Predictions for the Coming Decade: Yours

Hot Topics in 2020 Cosmology

dark energy, refinements of DM qualities/model

Non-Gaussianity, large scale structure and structure formation, neutrino cosmology, GRB cosmology, LHC related cosmology.

Something like String Theory that's not string theory; Cosmic Scalar fields... 5 more made up for random things

quantum theory of gravity or the nature of dark energy.

Analysis of and work on SUSY and GUT, along with their ramifications in our universe.... Research on inflation [...] with new help from Planck.

nature and properties of dark matter and dark energy, ... formation and evolution of large scale structures from density perturbations, and developing quantum gravity

dark energy will be the main topic

ten years isnt too large a chunk of time so really I expect [the questions] to largely remain the same...status report to remain relatively static. So the

CMB, theories relating to (quantum) gravity, dark energy, theories necessitating extra spatial dimensions to explain phenomena. Much ado about gravity. I expect neutrinos to be a big contender. Our work with them has really just begun and there is a general murmer rising regarding the electroweak scale. DM and DE vs cosmological constant.

Settled/Advanced Questions

detect DM & Higgs, determine value of w_Λ, solve Li problem

The existence of Higgs, non-Gaussianity and the model of GRB.

Existence of WIMPS; Higgs Boson; Source of neutrino masses; values of masses (big maybe!!!)

I'm hopeful that the Large Hadron Collider will have identified the magnetic monopole and the Higgs boson. WIMP nature of dark matter will have been solidified and that dark energy will be confirmed as a cosmological constant as opposed to quintessence.

physical proof for a good dark matter candidate that matches SUSY predictions, probably in CERN, and then verified in a CDMS experiment. We will be on the cusp of observations of gravity wave signal in CMB polarization. Planck will have given us much more accurate information about the CMB tilt, allowing analysis of the slow-roll parameters and inflation's properties.

I think the CMB polarization experiments (Planck, balloon flights, etc) will detect polarization caused by gravity waves resulting from inflation which will be one of the first independent confirmations that an inflationary period actually occurred. either [detect] the DM particle or have been sent back to the drawing board.

nature of the dark matter [...] determined by the LHC experiment, no matter what it is. Since there are so many candidates for DM today, I think at least one of them would be correct. So the DM problem will be solved.

I expect a lot of questions regarding the CMB to be handled by Planck... I suppose along with that come answers about structure formation.

Remaining Open/Unsettled Questions

nature of DE. quantum gravity/GUT

The nature of dark matter and dark energy.

Exactly what dark energy physically is. Planck scales (Theory of Everything); Scalar Fields; Vacuum Energy

While surveys like the Dark Energy Survey will confirm dark energy as a cosmological constant, the exact nature of this vacuum energy will continue to confuse and elude us by many orders of magnitude. The nature of the inflaton field will continue to be a mystery as well.

We won't know what dark energy is, though we'll have missions coming up that will help constrain the problem, and we will have killed modified gravity for good. We won't have direct gravity wave detections. We won't be peering past inflation or be able to say much about the physical cause of inflation.

Unanswered questions will be force unification and quantum gravity, a detailed understanding of structure formation, and the nature of dark energy since now we are only beginning to address these complex and difficult problems.

The dark energy problem (including the inflation) will remain unsolved. Even though the observational data seems to give us the LambdaCDM model, there are still a lot of models which give predictions very close to those of

LambdaCDM. The similar situation holds for the inflation. Even though we will have more data 10 years latter, I am pretty sure the data are not enough to give a unique model.

Anything regarding quantum gravity, or a unification of gravity with the other forces at all. I dont see this as the answer and I dont expect the graviton to be seen.

Surprises, both hopeful and cynical

GR breakdown (or at least addition to it)

Through people find the Higgs particle, it is not the dark matter particle. Then it challenges people to go beyond the standard model. On the observation side, it is still very difficult to pin down the equation of state of dark energy. But one theory comes out and unifies the dark energy problem with the generalization of quantum gravity.

Inflation (or parts of it) and Dark Energy are completely wrong. There is a definite, measurable curvature of the universe that entails a closed universe. Monopoles will be found. Current ideas of physics at high redshifts are wrong. Cosmic beer.

String theory will turn out to be a bunch of rubbish.

I cynically imagine that there is some other combination of factors that could combine to solve the same problems that inflation solves, and while we think we are constraining inflation, we are actually finding results that would actually make sense for this other solution.

I think we could be surprised that dark energy has some unexpected properties or that observations of some other standard candle (or better understanding of Type Ia SN) could reveal that the universe's expansion is not accelerating.

I imagine a toppling of the majority of efforts surrounding gravity, though Im not sure what would be able to do that within 10 years... I severely hope our understanding of DM and DE increases and, seeing as were rather clueless at the moment, I would expect more than one result to knock us over in those arenas.

I hope the DM particle found by LHC is something not in the standard model and not a SUSY particle. Then there will be a lot of works for particle theorists (and it will be easier for them to find a job, hopefully).

Predictions for the Coming Decade: Mine

For sure: a huge flood of precision data
"telescopes" from 30 m mirrors to LIGO to LHC
What will we learn?

Observations/Experiments

- dark energy evolution probed by DES, SNAP, Pan-STARRS, LSST, ...
- CMB T, polarization anisotropy to high precision
  inflationary gravity waves seen, plus non-gaussianity, ...
- deuterium in QSO absorbers to $< 1\%$: probe early U.
- cosmic 21-cm radiation detected over wide redshift range,
  probes structure, star formation
- Fermi (high-E γs) finds dark matter annihilation γs
- IceCUBE (high-E νs): extragalactic sources seen (AGN?)
- X-ray observations probe structure, state of intergalactic baryons
- β-decay experiments detect ν mass
- Webb (NGST): supernovae from first stars (Pop III) imaged
- gravity waves detected from NS/NS merger, associated with γ burst
- Higgs boson discovered (origin of electroweak mass)
- completely unexpected result(s) makes some of the above look naive

My Fondest Cosmological Wish for the Decade
The Dark Matter Trifecta

⋆ WIMP underground detectors find and confirm signal

⋆ LHC at CERN finds supersymmetric partners
consistent with WIMP evidence

⋆ γ-rays & radio see WIMP annihilation in Galactic center

Nobel prizes all around!

Theory

- supersymmetry detection leads to detailed inflation, baryogenesis theories
- dark energy motivates/constrains quantum gravity progress
- supernova models achieve successful explosions
  more confidence in Type Ia a cosmo probe
- chemical evolution models married with structure formation
  Galactic stellar abundances probe Galactic merger tree
- job security as unexpected new results challenge theorists

Into the Sunset

We are living in the golden age of cosmology

There is much more to learn
$\longrightarrow$ stay tuned to future colloquia, seminars, prelims, defenses!

Thank You!

Director's Cut Extras

The First Stars

Some sobering facts:

our understanding of local, resolved, high-metal star formation is at best incomplete

- birthplaces are molecular clouds
- most stars form in clusters, not isolated
- dust an essential ingredient `www: IRAS cores`
- magnetic fields present, surely important, possibly crucial
- mass distribution (IMF) strongly biased to low mass

theoretically: basic mechanism still debated

high-mass star formation especially poorly understood (rare objects, heavily enshrouded, rapid evolution)

but one must try, and besides ...

First Star Formation certainly different
exceedingly challenging observationally, but
maybe theoretically simpler?

- ⋆ no dust!
- ⋆ no/small magnetic fields?
- ⋆ no radiation, outflows, ejecta from previous stars
- ⋆ "first principles" initial conditions (environment, composition)

First Star Formation

Birthplaces: first collapsed halos containing baryons
hierarchical cosmic structure $\rightarrow$ lowest mass halos most common
smallest scale: baryonic Jeans mass a recomb: $\sim 10^6 M_\odot$

Composition: primordial–H, He, and Li only, no dust
lack of efficient coolants $\rightarrow$ hard to depressurize, collapse
only available molecules are H_2, traces of HD, LiH
$\rightarrow$ molecule formation (i.e., chemistry) critical in setting masses!

Abel Bryan & Norman (2001): cosmochemical simulations
one protostar per $10^6 M_\odot$ halo
inefficient cooling $\rightarrow$ slow evolution $\rightarrow$ accretion unimpeded
$\rightarrow$ massive star $\gtrsim 30 M_\odot$... but fragmentation?

conventional wisdom: first stars massive ($\gtrsim 10 M_\odot$)
bad news: none left today
good news: they don't go quietly! they do leave traces!

Population III Stars: Lifestyles

As usual, astro naming backwards (theorists dropped the ball)
- Population I: high-metallicity stars, disk distribution
- Population II: low-metallicity, halo distribution, kinematics
- Population III: zero metallicity, unobserved (to date!)

Stellar evolution sans metals

Massive star lives most strongly effects
- main sequence H burning normally via CNO cycle
  now must begin with $pp \rightarrow de\nu$ until self-enrich with CNO
- no metals in atmosphere $\rightarrow$ much lower opacity
  radiation-driven winds inefficient $\rightarrow$ less/no mass loss?
  difficulty stopping accretion

$\Rightarrow$ supermassive ($> 100 M_\odot$) stars possible?
- low opacity $\rightarrow$ more compact $\rightarrow$ faster rotation
  easier to make gamma-ray bursts?

Population III Stars: Death

As usual:
$\lesssim 10M_\odot$: AGB, PN, white dwarf
$\sim 10 - 30M_\odot$: supernova, neutron star
$\sim 30 - 50M_\odot$: supernova, fallback, black hole

But new twists:
$\sim 50 - 100M_\odot$: direct collapse to BH
$\sim 100 - 200M_\odot$: "pair instability," complete disruption!
$\gtrsim 300M_\odot$: direct black hole formation
nucleosynthesis patterns unlike "normal" supernovae

Open questions:
which masses actually created?
will very massive supernovae lead to superluminous explosions?
was a population of $\sim 10 - 100M_\odot$ black holes created?